Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **24**, 825–833 (1999)

PREDICTION OF RAINFALL-TRIGGERED LANDSLIDES: A TEST OF THE ANTECEDENT WATER STATUS MODEL

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Received 23 June 1997; Revised 22 December 1998; Accepted 1 March 1999

ABSTRACT

A rainfall-based landslide-triggering model, developed from previous landslide episodes in Wellington City, New Zealand, is tested for its ability to provide a 24-hour forecast of landslide occurrence. The model, referred to as the Antecedent Water Status Model, calculates an index of soil water, by running a daily water balance and applying a soil drainage factor to excess precipitation, over the preceding ten days. Together with the daily rainfall input, the soil water status has been used empirically to identify a threshold condition for landslide triggering.

The prediction process provides a daily update of the soil water status and thereby the amount of rainfall required on the following day to equal or exceed the triggering threshold. The probability that this triggering rainfall will occur is then determined from the frequency/magnitude distribution of the local rainfall record. The model produces a satisfactory level of prediction, particularly for periods of concentrated landslide activity. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: landslides; prediction; thresholds; triggering rainfall; water balance

INTRODUCTION

Prediction of landslide occurrence is not only a fundamental goal of hazard management but also a test of how well the process is understood. Forewarning of landslides may be provided in different ways. By far the most common approach is the recognition of landslide susceptibility from a spatial perspective (Crozier, 1995). This generally involves an investigation of geotechnical or geomorphic factors for the purpose of ranking terrain units on their potential to produce landslides. However, as Varnes (1984) observed, spatial susceptibility only partly represents the landslide hazard. The greatest challenge is the need to predict the occurrence of landslides in time.

This study aims to develop a methodology, using previously established relationships between climate and landslide occurrence, to provide a regionally based temporal prediction of landslide initiation for Wellington City, New Zealand. The year 1996 provided the first opportunity to carry out a comprehensive test of a landslide–climate model established for the particularly severe landslide episode of 1974 (Crozier and Eyles, 1980). This opportunity arose because the winter of 1996 produced the first major landslide episode in Wellington since the model was established. In addition, landslide data had become readily available from a newly established 24-hour recording system operated by the City Council to register details of landslides as they occur throughout the city.

The predictive model is applied to shallow rainfall-triggered, first-time slope failures within an urban environment. Its output is ultimately a statement of the probability of this type of landslide occurring somewhere within the city within the following 24 hours.

The types of landslide involved are generally small (about 30 m^3 on average), predominantly shallow, highly disrupted translational rock slides and debris slides. Observations indicate that the same types of landslide occurred during the test period in 1996 as at the time the model was developed (Eyles *et al.*, 1978).

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CCC 0197-9337/99/090825–09 $17.50

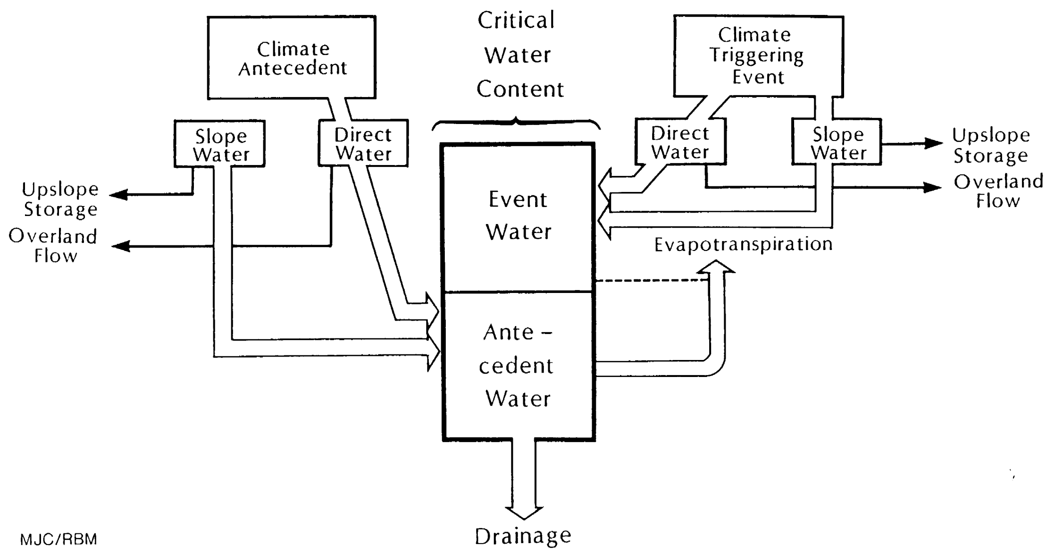

Figure 1. Conceptual hydro-climatic landslide triggering model

The city has been developed over a period of 150 years on steep greywacke terrain mantled with varying thicknesses of solifluction deposits, loess, residual soil and mixed slope deposits. Most of the landslides have occurred on road cuts and hillslopes varying in angle from 30 to 70°. The physical environment and landslide regime of the city has been described by Eyles *et al.* (1978) and Eyles and McConchie (1992).

THE MODEL

The conceptual basis for the Antecedent Water Status Model (AWSM) used in these predictions is illustrated in Figure 1 (Crozier, 1997). The fundamental assumption is that a critical water content (CWC) is required to initiate failure. Theoretically, the critical function of the water content relates either to its ability to reduce cohesion or its ability to increase buoyancy through positive porewater pressures, to an extent that the strength of slope material is lowered below the prevailing shear stress. However, recent research by Glade (1997) has shown that almost all major slope failures in this region occur at water contents in excess of field moisture capacity, indicating that the development of positive porewater pressures is critical for failure in this region. An important premise of the theoretical model is that CWC is composed of two components: 'antecedent soil water' and 'event water'.

An alternative approach employed in some regional climate/landslide research, involves the delimitation of triggering thresholds by using characteristics of the triggering storm such as rainfall intensity and duration (Caine, 1980; Brand *et al.*, 1984; Keefer *et al.* 1987; Julian and Anthony, 1994; Wilson and Wieczorek, 1995). Whereas some success has been achieved by this approach, particularly with the use of real-time rainfall values, it is limited in its ability to assess landslide probabilities prior to the triggering event. The choice of approach to climate landslide modelling needs to be based on a knowledge of which climatic parameters are most important in generating unstable conditions. Kim *et al.* (1992) (Figure 2) and Glade (1997) have demonstrated that, in certain regions, antecedent conditions have a major influence on the initiation of landslides, whereas in other regions, storm characteristics appear to dominate. The importance of accumulated rainfall in setting the conditions for shallow failure has also been established for a humid sub-tropical region by Garland and Olivier (1993).

In the empirical development of the AWSM, 'event water' is represented by the daily rainfall and 'antecedent water' is represented by the soil water status. Essentially, the soil water status is an index of the

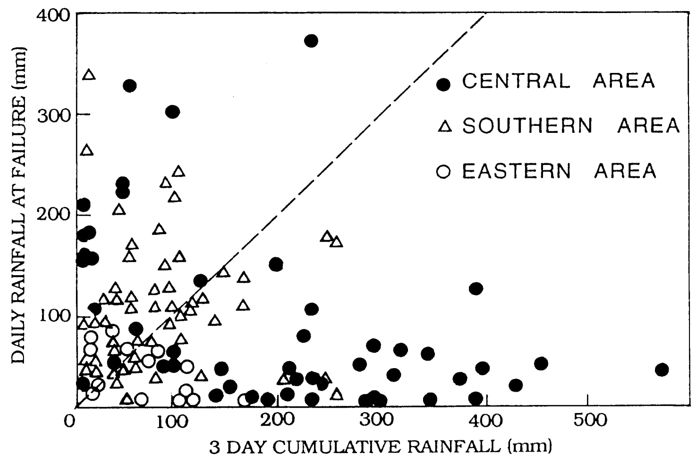

Figure 2. Relationship between daily rainfall at failure and antecedent rainfall, Korea (from Kim *et al.*, 1992)

water content of the soil based on the climatic water balance. Negative values of this index represent soil storage below field capacity, held in the form of capillary or hygroscopic water. Positive values are considered to represent gravitational water that accumulates as groundwater in certain slope locations (Crozier *et al.*, 1990).

Negative values of the soil water status index are expressed as deficit storage and are calculated as:

$$DS_0 = DS_1 - (P_0 - PE_0) \tag{1}$$

where DS_0 = deficit storage on day 0 (mm), DS_1 = deficit storage for the day before day 0 (mm), P_0 = precipitation on day 0 (mm), and PE_0 = potential evapotranspiration for day 0 (mm).

Positive values of the soil water status index are calculated from rainfall exceeding potential evapotranspiration and soil storage requirements:

$$EP_0 = (P_0 - PE_0) - DS_1 \tag{2}$$

where EP_0 = excess rainfal on day 0 (mm).

Excess rainfall is decayed on a daily basis and accumulated over a given period to represent antecedent excess rainfall values. These constitute the positive values of the soil water status index.

$$EPa_0 = kEP_1 + k^2EP_2 \ldots + k^nEP^n \tag{3}$$

where EPa_0 = antecedent excess rainfall on day 0 (mm), EP^n = excess rainfall on the nth day before day 0 (mm), and k = constant decay factor.

In order to calculate the soil water status, assumptions must be made on the regolith storage capacity (porosity and depth), evapotranspiration rates, and the drainage rate of excess precipitation. The AWSM, as used here, calculates antecedent soil water status from pan evaporation rates, daily rainfall, and a soil moisture storage capacity of 120 mm. Daily precipitation in excess of soil storage requirements and evaporation demand is drained exponentially over a period of 10 days, using a decay constant of 0·84. The excess decayed rainfall is then accumulated over 10 days to provide the antecedent soil water status index to be applied to the following day.

Research leading to the development of the model is discussed by Crozier (1989). Ongoing research (Glade, 1997) is aimed at deriving a more comprehensive set of parameters for this model, based on recorded physical processes and properties applicable to the region.

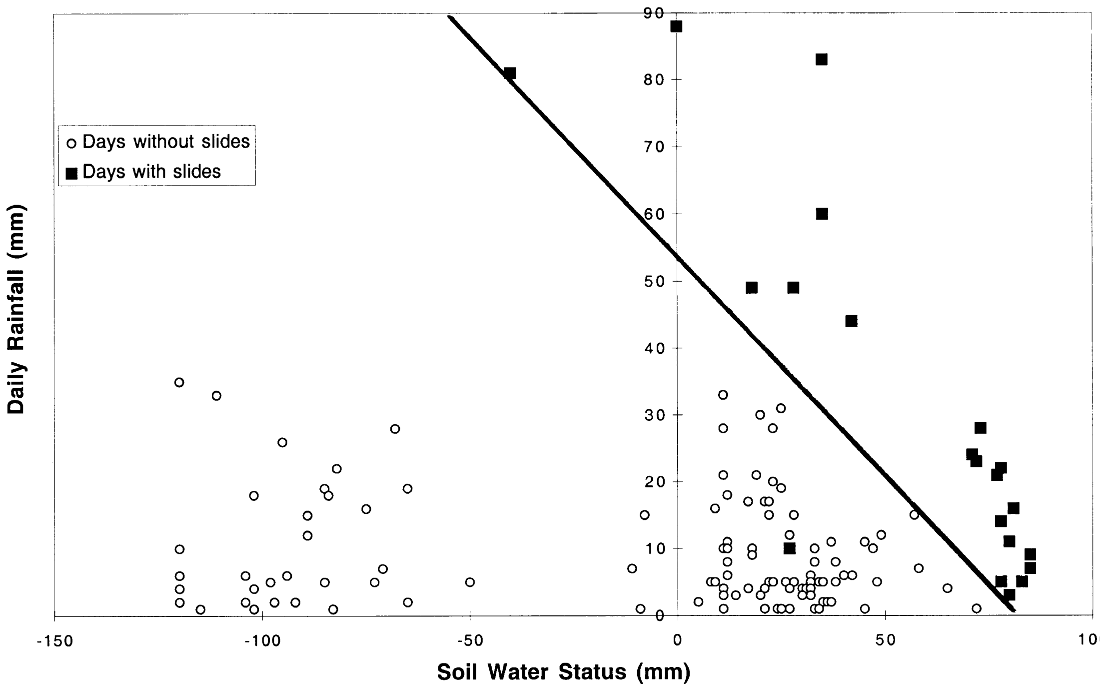

Figure 3. Maximum landslide triggering threshold for the 1974 landslide episode, Wellington City, New Zealand

The aim of the model is to examine climatic conditions in conjunction with landslide events in order to differentiate those conditions associated with landslides from those not associated with landslides. However, there are major limitations in establishing empirical models of this sort. The principal problems relate to the recording of the timing both of storm rainfall and landslide occurrence, the difficulties of trying to represent site conditions from regional parameters, and the regional applicability of point climatic values. Nevertheless, the AWSM was able to achieve a clear discrimination between landslide and non-landslide conditions for the 1974 episode (Figure 3). The threshold shown on this figure is the 'maximum' threshold above which combined soil water status and rainfall values have always been associated with landsliding in the event record (see Crozier (1989) for a discussion of threshold types). It should be noted that the landslide events used to develop the threshold for the 1974 episode have no magnitude connotation other than that they were considered to be 'significant', for example, by causing traffic disruption within the city. This model of triggering conditions is tested here as the basis for predicting landsliding in 1996.

METHODOLOGY FOR PREDICTION

The predictive procedure was carried out by applying simple programming routines within Visual Basic (© Microsoft Corporation) to a spreadsheet data base. The soil water status was updated each day using a water balance routine with input variables of daily evaporation and daily rainfall, provided by the National Institute of Water and Atmospheric Research, for the Kelburn meteorological station. This station is the same one used to develop the 1974 model and is located at an elevation of 125 m a.s.l. within the hillslope suburbs of Wellington. The constants used in the calculations were soil water storage capacity and a drainage function, as described above. This provided daily information on soil moisture storage, rainfall surplus (excess precipitation), and ultimately antecedent soil water status (Figure 4).

Each day the soil water status was automatically entered into a linear regression model representing the landslide triggering threshold shown in Figure 3, in order to calculate the amount of daily rainfall required to

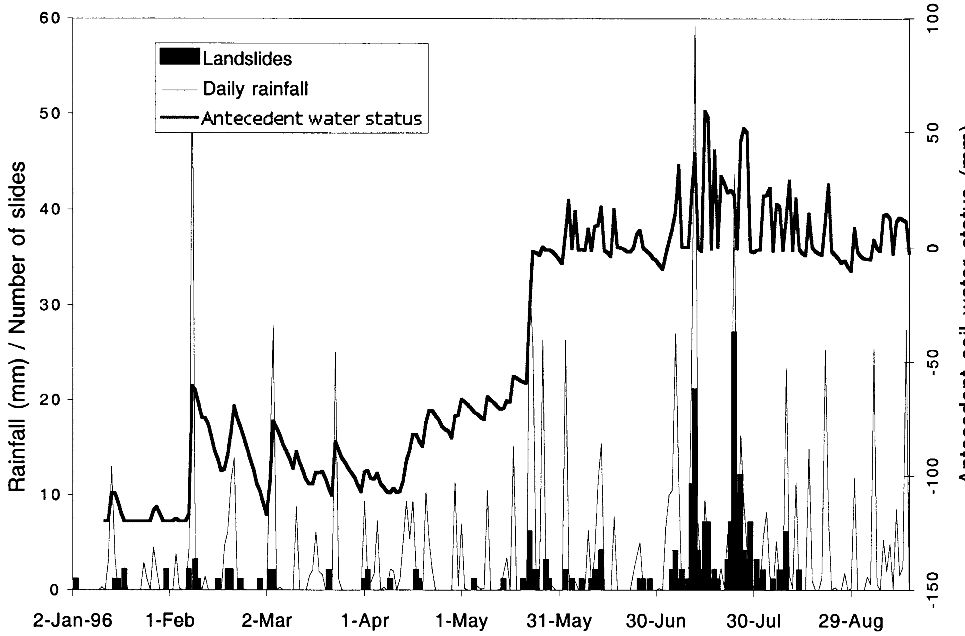

Figure 4. Daily rainfall and landslide occurrence in relation to the modelled antecedent water status, Wellington City

equal or exceed the threshold on the following day (Figure 5). The probability that the required triggering rainfall on any given day will be equalled or exceeded is determined by applying the required value to the frequency/magnitude relationship of Wellington rainfall. The frequency magnitude of Wellington rainfall used to determine probabilities was calculated by Glade (1997) using over 26 000 daily rainfall values by combining records of 20 stations within the Wellington region. The percentage probability of occurrence (*Y*) for a given rainfall depth in millimetres (*X*), on any one day, somewhere within the region is given by the equation:

$$Y = -16 \cdot 66 \text{ Log } X + 35$$

Although this equation is considered accurate for the rainfalls used in the period of model validation, extreme values will be better represented by a relationship of the form:

$$Y = A \exp{(-X/B)}$$

The highest probability on any one day cannot exceed 54 per cent because on average rain occurs somewhere within the region on only 196 days in the year.

The predictive capability of the AWSM model is illustrated in Figures 6 and 7.

PREDICTIVE PERFORMANCE

In regions such as Wellington, where antecedent soil water represents an important precondition for slope failure, there is an opportunity to provide a realistic forewarning of landslide occurrence. Figure 4 shows that through autumn there is a build-up of soil water and a rapid shift to winter conditions where soil water status is near or above field capacity (zero on the antecedent soil water status scale). While there is a background level of slipping throughout the year, significant landsliding, represented by contiguous days with three or more recorded landslides, does not occur until the antecedent water status index is above zero.

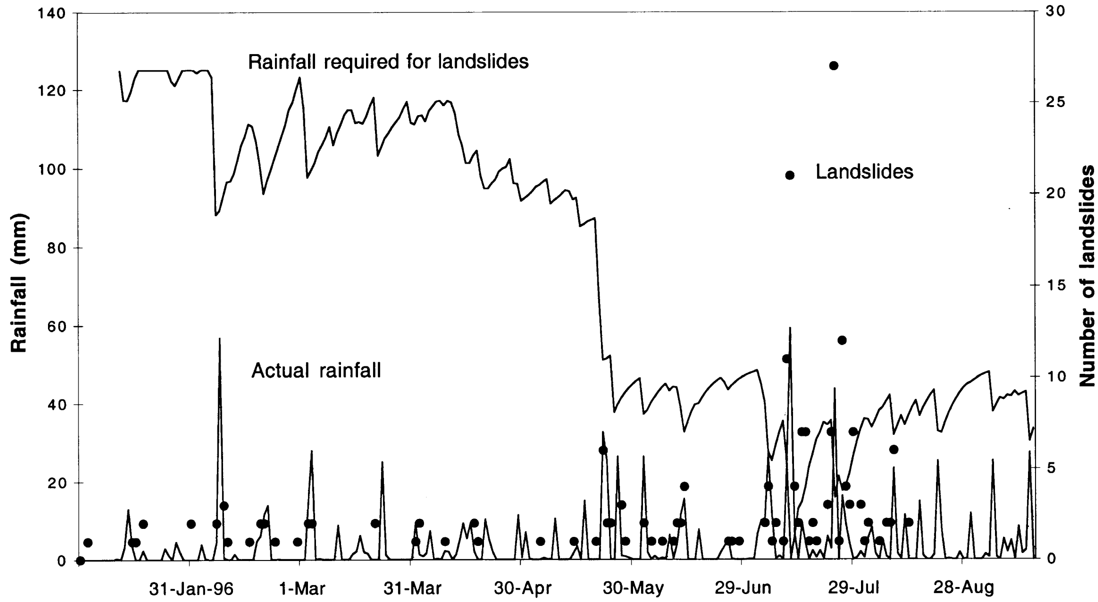

Figure 5. Relationship between predicted and actual conditions of landslide occurrence, Wellington City

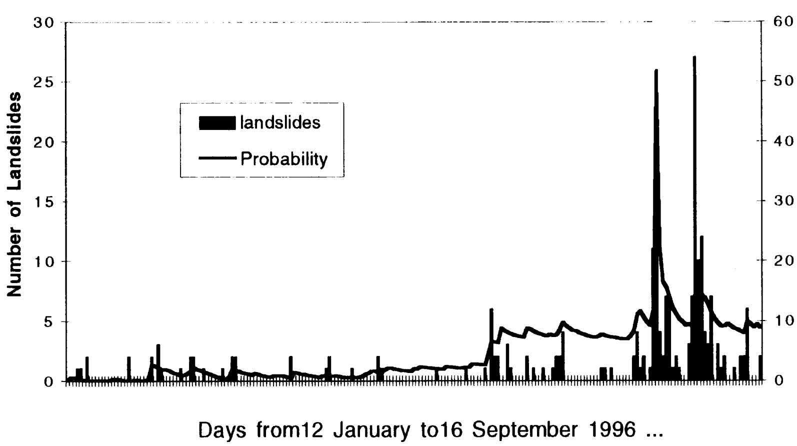

Figure 6. A time series of the probability of landslide-triggering rainfall occurring within 24 hours and the occurrence of landslides, Wellington City

The two major episodes of landslide activity which peak at over 20 landslides a day and involve continual landsliding for several days are both predicted in Figure 5, at the points where actual rainfall is shown to exceed the rainfall required to produce landslides. Other less significant periods of landsliding are not as well predicted by the model. The reason that not all 1996 landslides are predicted by the model in part relates to the differences in criteria for recording landslides. In the original model only significant landslides, that is traffic blocking or otherwise disruptive landslides, were used to identify the threshold, whereas in 1996 all landslides, whatever their size or significance, have been plotted on the figures. Accordingly, the 1996 threshold is lower than that determined for 1974 (Figure 8).

Figure 6 represents the daily probability of landslides occurring ‘tomorrow’ throughout the validation period. In general terms, this probability forecast has identified susceptible landsliding periods. Absolute probability values related to actual landslide occurrence suggest that a probability of 10 per cent or more

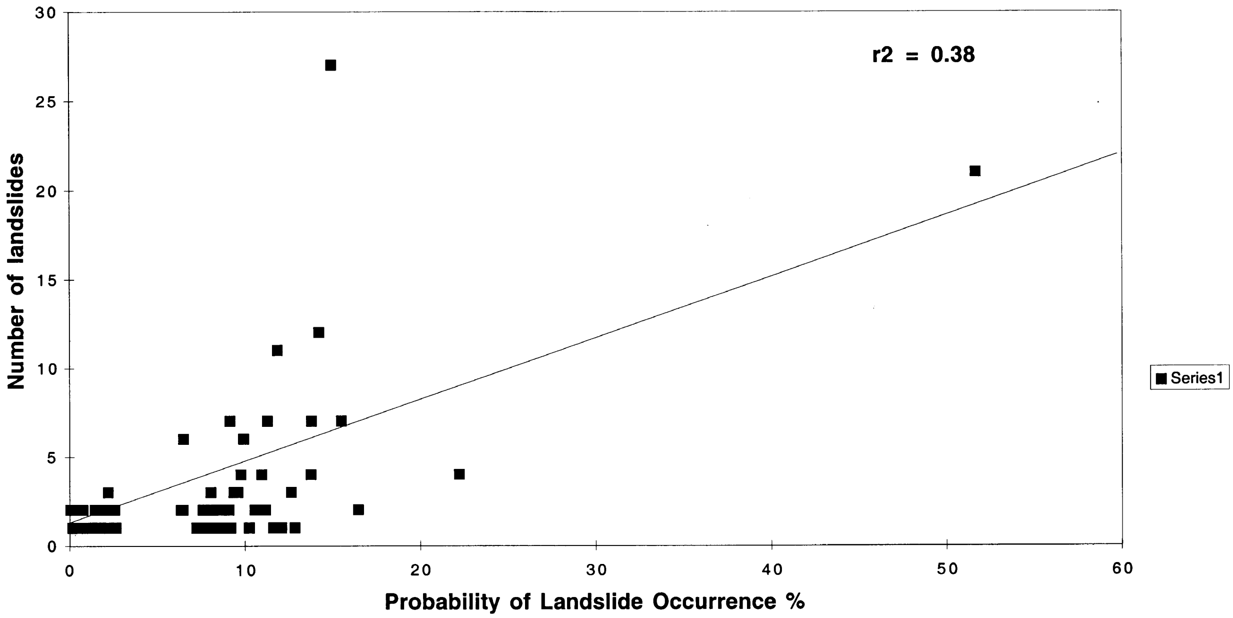

Figure 7. Probability of landslides occurring within the following 24 hours versus the number of landslides that actually occurred

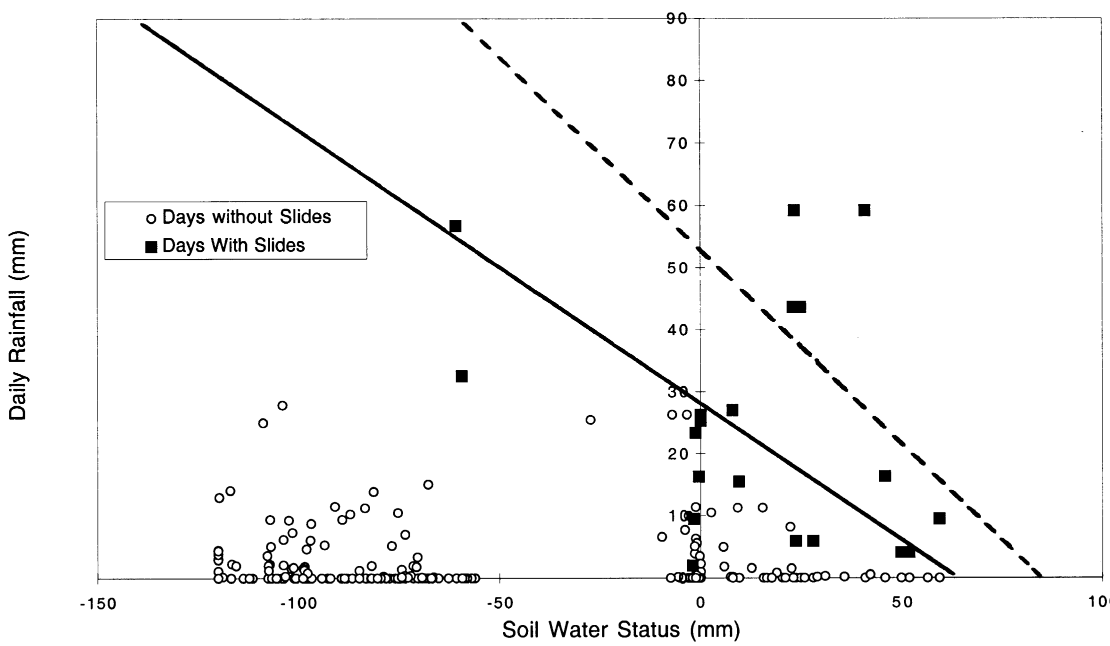

Figure 8. Maximum landslide triggering thresholds for 1996 (solid line) and 1974 (broken line)

should provide an alert to significant landslide activity. Clearly a 10 per cent probability is not likely to engender much concern and a more realistic approach to probabilities is required. The greatest potential for this lies in tying the model into synoptic weather conditions and weather forecasts.

Whereas the forecasting process can indicate the occurrence of significant landsliding over the following 24 hours, its ability to provide a quantitative prediction of landsliding is less well defined. Figure 7 indicates that the probability factor can only account for about 38 per cent in the variability of the numbers of landslides, on days that landslides occur.

Figure 8 compares the AWSM-derived threshold using 1996 data for days that produced three or more landslides with the threshold derived from the 1974 event. The difference in the two thresholds may reflect the criteria used to select landslides for inclusion in the analysis, as mentioned above, or alternatively, it may reflect physical changes occurring within the slope environment (Crozier and Preston, 1999). What is more, a regional approach, as used here, provides a level of abstraction which can only provide an approximation of the factors which directly control the initiation of slope failure.

CONCLUSION AND DISCUSSION

The Antecedent Water Status Model applied to Wellington has been able to provide a potentially useful level of prediction for the occurrence of landsliding, particularly for periods of significant activity. However, in a regional approach, such as used here, precision in prediction may be limited by a number of factors. Foremost of these is the ability of the model to produce a threshold which discriminates exclusively between triggering and non-triggering conditions. The question of confidence limits of thresholds has been discussed elsewhere (Crozier, 1996). In the current predictive test, this problem has been minimized by adopting the maximum threshold. The maximum threshold represents conditions which, when exceeded, have always produced landslides. Generally a minimum threshold can also be recognized below which landslides have never been recorded. In between these two thresholds there is a probability range where landslides may or may not occur. Because of the broad relationship that is generally found between the magnitude of the triggering agent and the degree of response (Eyles and Eyles, 1982; Omura and Hicks, 1992), it is likely that much of the ambiguity within the probability range could be reduced if thresholds were established with reference to a particular magnitude of landsliding. By using the maximum threshold, the biggest events are being predicted with most confidence, but smaller landslides associated with higher probability triggering conditions are ignored.

The extrapolation of point data to represent regional conditions and the prediction of site conditions from remotely recorded values is, by nature, a problem implicit in many regional studies and is clearly related to the size of the region and homogeneity of physical conditions. These problems, together with the calculation of more representative, physically based parameters for use within the model, are addressed by Glade (1997). The question of prediction of unstable locations has not formed part of this study. However, the problems sites within the city are well known and it is these areas that could be profitably monitored at times when the AWSM indicates a high probability of landsliding. Because of landslide potential during major earth works on steep hillslopes, territorial authorities could make reference to the AWSM when setting conditions on land use consents, prohibiting certain activities when high landslide probability is indicated.

ACKNOWLEDGEMENTS

Bob Eyles and Ralph Wheeler contributed much to the original conceptual approach for this work. My thanks also to two anonymous reviewers for their helpful comments.

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